SHOCKTUBE PLANAR LASER INDUCED FLUORESCENCE MEASUREMENTS IN SUPPORT OF THE AEDC IMPULSE FACILITY*

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Abstract

This paper describes the status of a program underway at AEDC to develop the Planar Laser Induced Fluorescence (PLIF) method of measurement of temperature and number density for use in the AEDC Impulse Shock Tunnel Facility. The technique is being developed in a laboratory shocktube environment which economically provides repeatable, well-characterized flow fields. A laboratory of this type is critical for the demonstration, validation, and calibration of facility diagnostics systems. PLIF nitric oxide images in shocktube flows for selected incident Mach numbers between M_S = 2.0 and 2.5 and temperatures between 1,000 and 1,500 K for spherical, 30-deg half-angle cone, and 10-deg half-angle blunt cone model geometries are presented. PLIF nitric oxide images of the flow field around a 10-deg half-angle blunt cone recorded during initial runs of the Impulse Facility are shown. Emission spectroscopy measurements in the nose cone bowshock region of the model in the AEDC Impulse Facility flow field are reported.

Introduction

The AEDC Impulse Facility is a free-piston reflected shock tunnel (light-gas gun) capable of generating high-enthalpy and high-pressure stagnation conditions. The facility provides a flow that significantly expands the current U.S. ground test capability in the high-velocity chemical nonequilibrium regions of the flight corridor. Free-stream total number densities ranging from 1×10^{16} to 3×10^{17} molecules/cm^3 at static temperatures from 500 to 2,800 K, and flow velocities from about 4 to 6.5 km/sec can be generated.

The hypersonic flow generated by the Impulse Facility is of interest for validating CFD models incorporating high-temperature gas kinetics. The test gas usually consists of dry air. Because of the high temperatures generated, considerable amounts of nitric oxide (NO) and atomic oxygen (O) are produced in the expanded shock-heated flow. Since the amounts of NO and O generated are good indicators of the complex chemistry of the flow process, it is important to measure their concentrations. Planar laser-induced fluorescence (PLIF) is an excellent technique for measuring the global distribution of NO in a flow field.[1,2] A sheet of ultraviolet laser light tuned to an NO absorption transition produces a sheet of fluorescing NO molecules. The fluorescence is recorded by an Intensified Charge Coupled Device (ICCD) array camera. This technique was previously applied to the wake region of a free-flight hypervelocity projectile in the AEDC Range G,[3] and has recently been used in the AEDC Impulse Facility during a series of checkout runs to examine the flow about a 10-deg stainless blunt cone model with a copper nose tip.[4,5] The image in Fig. 1 clearly indicates the presence of NO (note that there is no signal in the shadow region at the bottom of the model); however, other sources of light are also present. This additional radiation has also been observed by Beck, et al.[6] The limited amount of test time available prevented background (laser off) runs; thus, quantitative analysis and interpretation of the PLIF image in Fig. 1 was severely restricted. Indeed, the difficulties encountered in interpreting the image of Fig. 1 made it clear that a dedicated laboratory facility for system operational checks, calibrations and validations was absolutely necessary. Furthermore, the future need for atomic oxygen diagnostics made a shocktube facility the obvious choice.

Laboratory Shocktube

Shocktube facilities are useful for studying high-temperature gas dynamic phenomena because they provide a localized region of high-temperature, high-pressure gas at well-known conditions in an acces-

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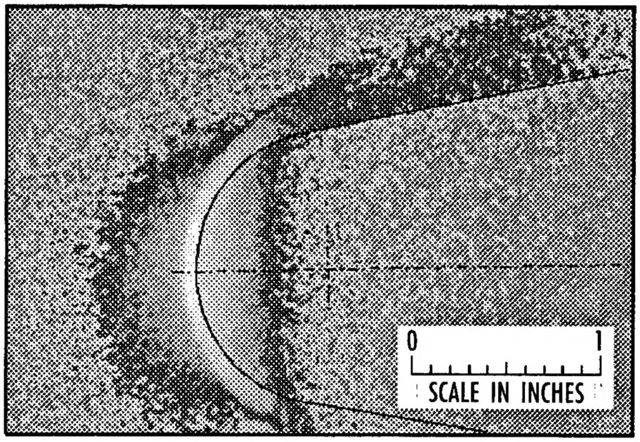

Figure 1. PLIF nitric oxide image from AEDC Impulse Facility run 13.

sible, easily operated laboratory device. AEDC's shocktube was constructed in the 1970's and was last used for research in 1985. It was refurbished and returned to operational status in 1993 to support the validation and calibration of aerodynamic flow diagnostics being developed for use in the AEDC Impulse Facility. The shocktube (Fig. 2) consists of two chambers separated by a double diaphragm: a high-pressure driver section and a low-pressure driven (test gas) section. The diaphragms are constructed from soft aluminum and are scribed to produce repeatable and uniform ruptures. For the subject tests, the driver gas was helium, and the test gas consisted of a nitric oxide/nitrogen (NO/N_2) mixture. A temperature range of $800 \leq T \leq 4{,}000$ K, a number density range of $5.0 \times 10^{18} \leq n \leq 6.0 \times 10^{19}$ molecules/cm^3, and a Mach number range of $2.5 \leq MS \leq 6$ are achievable in the shocktube.

When the firing sequence is initiated, a fast-operating solenoid valve releases the helium between the diaphragms into a dump tank, causing a sudden pressure differential and rupturing the diaphragm adjacent to the high-pressure driver gas. The arrival of the high-pressure gas at the second diaphragm causes it to rupture and initiates a shock wave which propagates into the low-pressure test gas, thereby increasing its temperature and pressure.

Fast piezoelectric pressure transducers (Kistler® model 603B1 transducers and model 5004 charge amplifiers, having a frequency response of 500 kHz) detect the shock front as it propagates down the length of the shocktube. A 486/50 MHz PC-based data acquisition/control system was developed to record the pressure transducer signals, calculate the shock velocity and deceleration, and generate timing triggers for diagnostic instrumentation. The system software allows the measurement timing with a precision of a few microseconds. The entire sequence from firing to helium arrival at the test section occurs in approximately 3 msec.

The shocktube test section consists of two chambers whose inner diameters match the inner diameter of the shocktube, thereby minimizing flow disturbances. The smaller chamber has four circular ports, equally spaced around the circumference, at the same axial station. Four rectangular ports are arranged similarly for PLIF diagnostics in the larger chamber. All port windows are made of synthetic fused silica (Suprasil® II). Available test time in the incident shock is approximately 100 µsec. Turn-around time is approximately 15 min per shot.

Experimental Setup

The laser system used at both the Impulse Facility and the shocktube consisted of a Spectra Physics® Model GCR-4 Nd:YAG laser, a Model PDL-3 tunable dye laser, and a Model WEX-2 wavelength extender. The Nd:YAG laser, whose infrared beam was frequency doubled, pumped the dye laser. The dye laser's output was frequency doubled and difference mixed with a portion of the Nd:YAG laser's infrared beam in the wavelength extender to yield a 1 - 2 mJ pulse at a wavelength of nominally 226 nm and a bandwidth of nominally 1 cm^{-1}. Nitric oxide absorbs at this wavelength, thereby exciting the NO $A \leftarrow X$ γ bands. The laser/diagnostics setup is shown in Fig. 3. Wavelength tuning was accomplished by monitoring the LIF signal generated when a portion of the laser beam was diverted through a reference cell containing a NO/N_2 mixture with a NO number

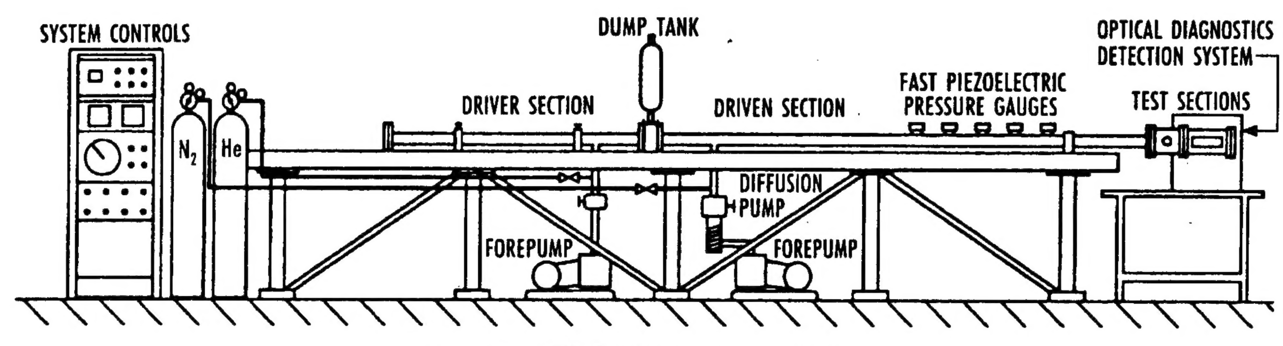

Figure 2. AEDC laboratory shocktube.

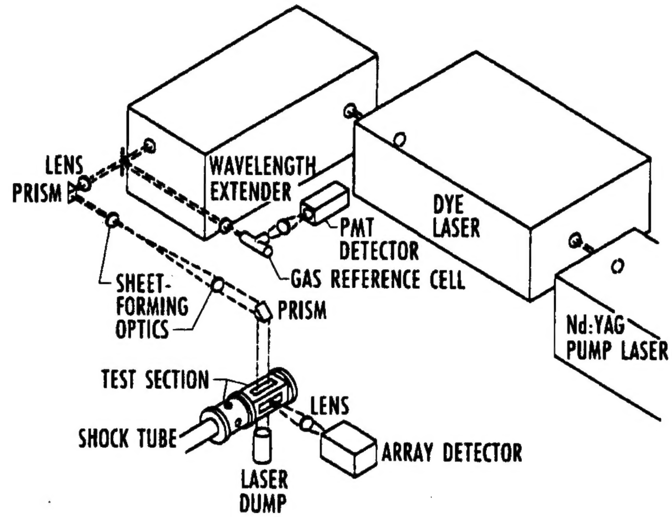

Figure 3. PLIF laser and diagnostics setup at shock-tube.

density of 2 × 10^{11} molecules/cm^3 and a temperature of 300 K. A typical excitation spectrum, obtained by tuning the dye laser over the range from 225.4 to 227.0 nm, is shown in Fig. 4. The transition used for the PLIF measurements was the $R_{11}(13)$ 225.716-nm line, which is identified in Fig. 5. This transition was selected because its absorptive strength is strongly temperature dependent in the range of interest, nominally 1,000 K - 2,000 K, and because of its relative isolation from neighboring transitions.

The 226-nm laser light was formed into a thin sheet (50-mm wide by 0.5-mm thick) using a spherical lens and a cylindrical telescope. The resultant NO fluorescence was imaged onto a two-dimensional ICCD camera (Princeton Instruments® ICCD 576S/RB 576 × 384 pixel intensified array) using an f/4.5 Nikkor® UV lens. An Acton® ARC-254 bandpass filter (50 nm bandwidth centered at 254 nm, 30-percent peak transmission) and a Schott® UG-5 glass filter (175-nm bandwidth centered at 300 nm, 90-percent peak transmission) were used to eliminate Rayleigh and room light. The 254-nm filter was also used because the UG-5 filter cuts on again near 650 nm, and emission in the red region of the spectrum could not be ruled out in the Impulse Facility flow field. The data acquisition, processing, and control of the camera were provided by a Princeton Instruments ST-130 controller and CSMA© software operating on a 486/PC system.

To assure maximum laser system energy output for a single pulse, the Nd:YAG laser was continuously pulsed at a rate of 10 Hz. This kept the Nd:YAG laser rods hot and the frequency-mixing crystals warm. Only one pulse could be generated for each shocktube firing. A pre-fire trigger from the shocktube firing circuit interrupted the laser approximately 100-120 msec before the arrival of the flow. This interrupt trigger was generated when the shocktube firing sequence was initiated by a relay which was energized when the double-diaphragm solenoid valve was activated. The data acquisition/control system generated the laser-firing trigger at the appropriate time based upon pressure transducer velocity calculations. The average velocity between pressure transducers and the laser fire time were recorded.

PLIF images have been obtained in the shock-tube for a variety of model geometries and flow conditions to aid in the development of a general calibration scheme for the Impulse Facility. Shown in Fig. 6 is a PLIF image of the flow past a 3/8 in.

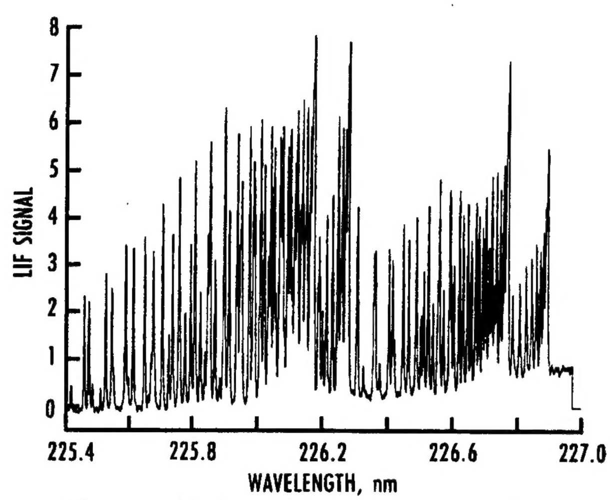

Figure 4. Nitric oxide excitation spectrum.

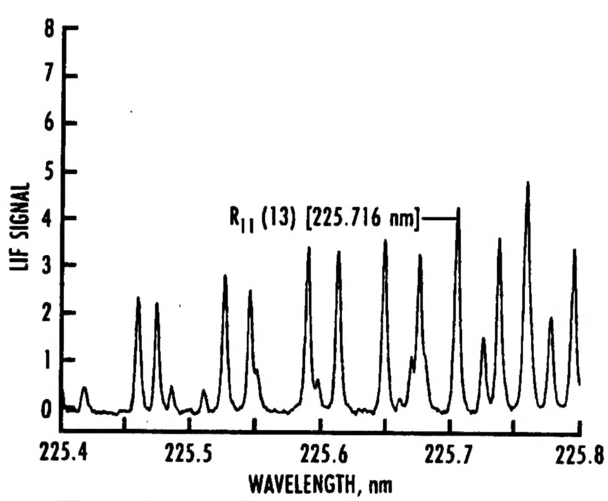

Figure 5. $R_{11}(13)$ transition of nitric oxide.

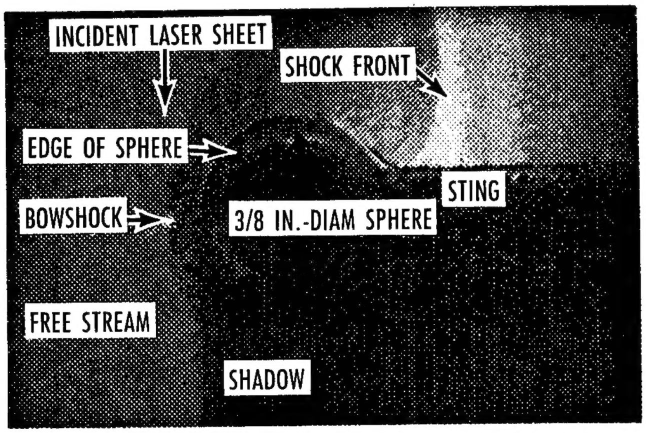

Figure 6. PLIF image of 3/8-in. spherical model.

spherical model at an incident Mach number of 2.4, a free-stream temperature T $\simeq$ 1,350 K, a total free-stream number density of 2 $\times$ 10^{19} molecules/cm^3, and a shock velocity of approximately 1,580 m/sec. Note the uniform free-stream conditions and the visibility of the edge of the shockfront. This illustrates the need to know the exact fire time to assure that the flow is fully established. Figure 7 is a PLIF image of the flow about a 30-deg half-angle cone at similar conditions.

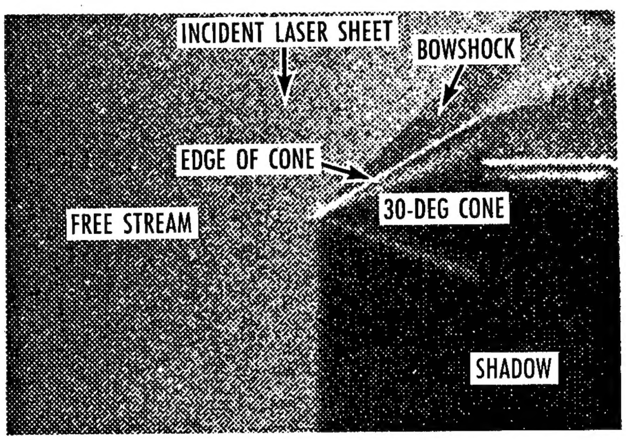

Figure 7. PLIF image of 30-deg conical model.

The flow over a scaled-down section of the 10-deg blunt cone used in the Impulse Facility checkout runs (Fig. 1) is shown by the PLIF image in Fig. 8. The flow Mach number was approximately 2.1, and the free-stream temperature and number density were 1,100 K and 2.3 $\times$ 10^{19} molecules/cm^3, respectively. Note the well-defined bowshock. The additional shock at the top of the image originated from the leading edge of the recessed rectangular window port. The model was subsequently moved upstream of this window shock, and a PLIF image at the new position is shown in Fig. 9 for a Mach 2.2 flow at a free stream temperature of T $\simeq$ 1,380 K. A portion of the window shock is still visible in the upper right hand corner. The decrease in fluorescence seen in both figures as the flow progresses from the freestream into the bowshock region is attributed to the dominating influence of the N_2 molecule collisional quenching of the NO fluorescence. Paul, et al,[7] have found the quenching by N_2 to increase rapidly with temperature.

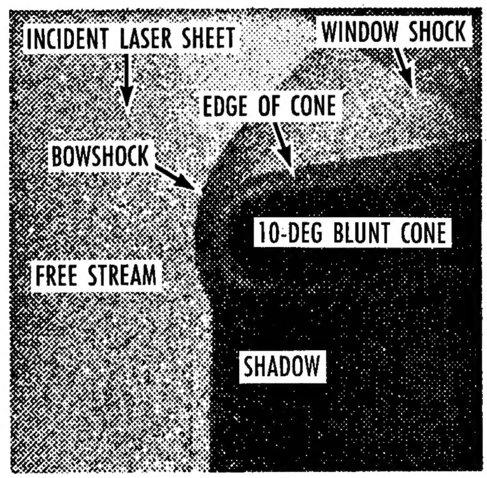

Figure 8. PLIF image of 10-deg half-angle blunt cone model.

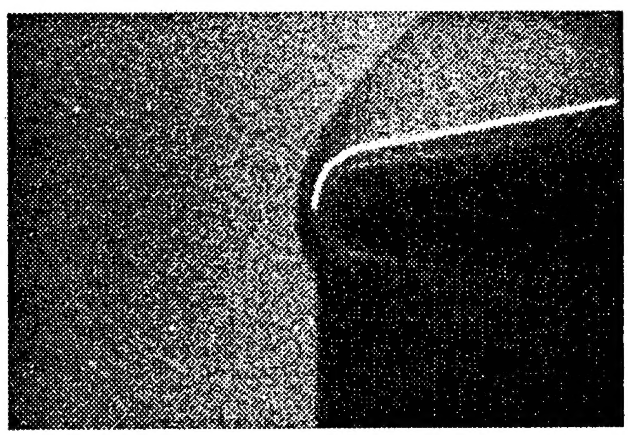

Figure 9. PLIF image of 10-deg half-angle blunt cone. model.

The shocktube flow conditions and NO mole fraction were set to produce NO number densities and temperatures similar to those expected in the Impulse Facility. Consequently, detector gain settings could be anticipated for planned Impulse Facility flow conditions.

Impulse Facility Measurements

A similar experimental setup was used at the Impulse Facility, with the exception that a 100-mm-wide $\times$ 0.5-mm-thick sheet and a more sophisticated triggering system were required. Because of the

small amount of time from facility fire until the establishment of flow at the nozzle exit plane (approximately 100 msec for the test conditions used), a prefire interrupt trigger was generated from the countdown sequencer to initiate the laser firing timing sequence. The prefire trigger, used to interrupt laser pulsing, was issued 25 msec prior to the firing of the Impulse Facility. An additional trigger pulse, generated by the rupture of the diaphragm separating the shocktube from the nozzle, was used as the timing reference point to charge and fire the laser. Flow was established at the nozzle exit approximately 400 - 600 μsec after this trigger. The firing of the laser was delayed an additional millisecond to assure that the flow was fully established.

The positioning of the laser sheet for the PLIF image shown in Fig. 1 was based on a desire to obtain as much information as possible about free-stream and bowshock regions. The magnitude of the UV radiation in the nose bowshock region was not expected; thus, the source of the radiation was investigated by recording spatially resolved emission spectra in the bowshock region. An ICCD 576 S/RB camera was mounted to the exit plane of an Acton 0.275-m spectrometer. A 25-μm entrance slitwidth was used, and a spectral resolution of 0.03 nm was obtained. The entrance slit height was 10 mm, which was equivalent to a length of 20 mm in the flow, oriented at a slight angle to the flow centerline. The ICCD camera had a 250-μsec gatewidth, and examples of the recorded spectra are shown in Figs. 10 and 11. Analysis of the spectra identified atomic iron and chromium lines, and these were attributed to flow contaminants produced by erosion in the Impulse Facility throat region.

A future investigation will determine if the interfering radiation can be subtracted from the image using a second identically aligned and gated ICCD camera, just prior to the laser firing. In the interim, the system was repositioned to record PLIF images further downstream on the cone model, at the locations shown in Fig. 12. The resultant images for Impulse Facility runs 15 and 16 are shown in Figs. 13 and 14, respectively.

Close examination of Fig. 13 reveals hyperbolic-shaped features resulting from the PLIF cut across the parabolic bowshock and the flow structure along the cone surface. An interesting feature is seen in Fig. 14 in the local model flow field. The fluorescence level increases across the bowshock, indicating that the quenching effect observed in the laboratory shocktube flow field is considerably reduced. This is most likely caused by the much lower N_2 density.

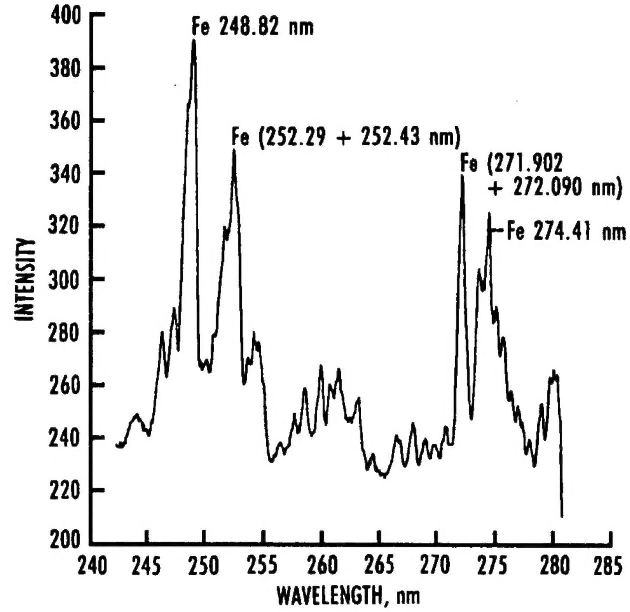

Figure 10. Impulse facility emission spectrum.

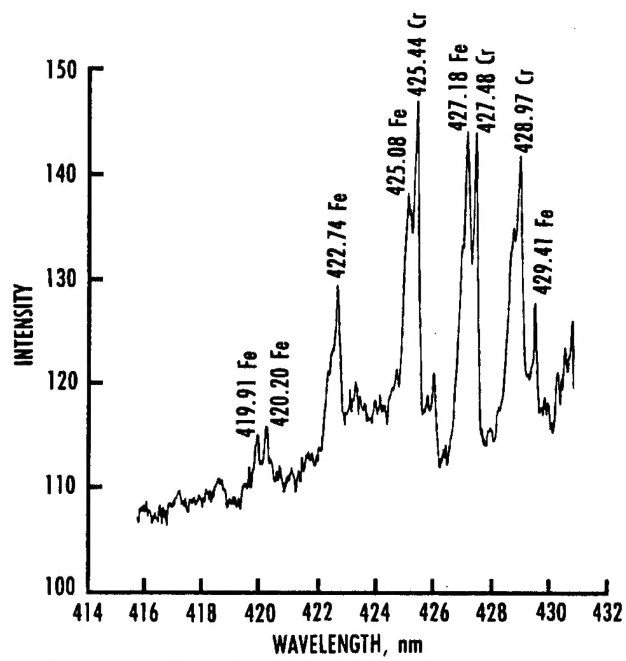

Figure 11. Impulse facility emission spectrum.

Also, the region of lower intensity near the middle of the bowshock matches predictions; however, the intensity should continue to decrease as the model surface is approached. These effects are described further in another paper at this meeting.[8]

Computational Modeling

The tests described in this paper were guided by static calibrations and numerical predictions of the comprehensive AEDC computer code LIFNO, which predicts measured fluorescence signal levels for a given CFD solution of the flow field. The code uses

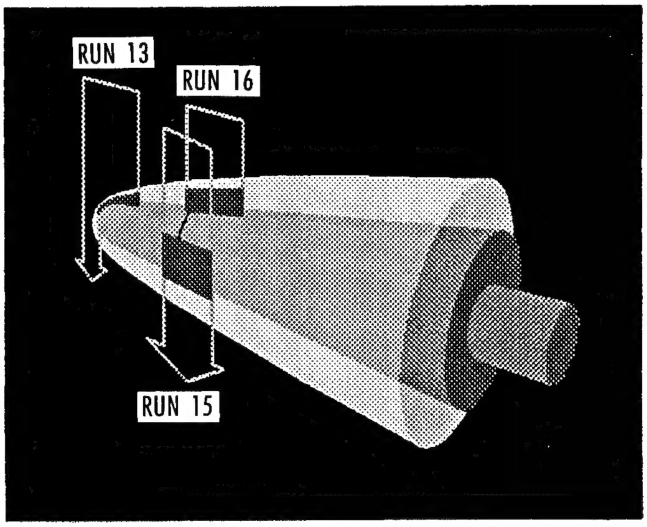

Figure 12. Spatial locations of Impulse Facility PLIF images on runs 13, 15, and 16.

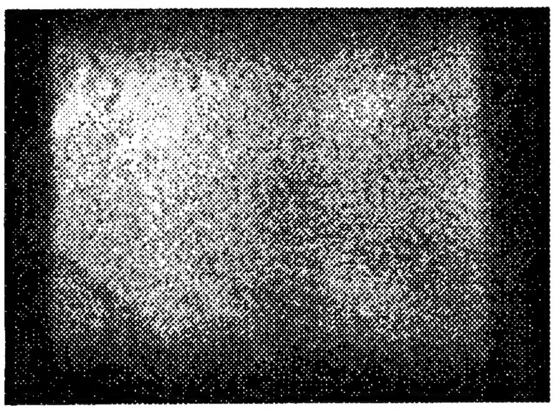

Figure 13. AEDC Impulse Facility run 15 PLIF image.

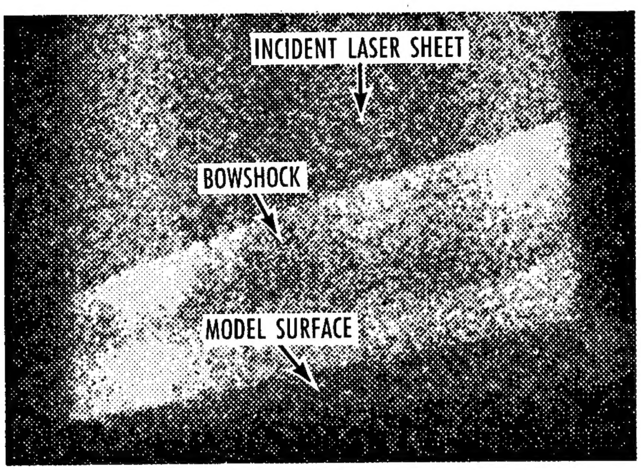

Figure 14. AEDC Impulse Facility run 16 PLIF image.

known spectral parameters and convolution of the laser lineshape with absorption lineshape, and it contains models of absorption line pressure and Doppler broadening and shifting as well as temperature-dependent collisional quenching for species such as NO, N_2, O_2, and O. Inputs to the code include laser wavelength, energy, and lineshape, optical element and detection system parameters, and flowfield gas parameters. CFD predictions have been used to provide gas parameter inputs resulting in computational flow images (CFI) for comparison to PLIF images.[8] With the exception of unanticipated nose emissions and the increased signal levels close to the model surface in Fig. 14, the results are consistent with calculations.

Summary

PLIF NO images have been obtained in incident shock flow fields for spherical, conical, and blunt conical aerodynamic models in a laboratory shocktube. The PLIF system has also been applied to the large-scale AEDC Impulse Facility, and initial PLIF images from the facility calibration runs have been shown. Intense UV flow radiation from iron and chromium found in the bowshock region of the Impulse Facility model seriously impairs the determination of quantitative NO density and temperature parameters without the corrective methods proposed. Further analysis of the PLIF images is presented elsewhere at this meeting.[8]

Future work consists of application of a dual-pulse, dual-wavelength PLIF system in the laboratory shocktube to provide simultaneous measurement of both temperature and NO number density. The dual-line technique will then be implemented in the Impulse Facility, contingent upon favorable results in the shocktube.

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